Modelling Ultra-short Pulse Laser Ablation of Dielectric Materials Using Multiple Rate Equations

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Abstract

Ultrafast lasers are widely applied in micromachining, material science and physics. In industry, picosecond lasers are becoming more and more established. For pulse lengths shorter than the electron-phonon coupling time, heat affected zones are negligible. Thermally sensitive materials can be processed using ultrashort pulse laser radiation. Multi-component materials and poorly absorbing materials can be ablated through the exploitation of nonlinear absorption processes making absorption nearly material independent.

Modelling of ultrafast laser-material interaction has been investigated for pulse lengths well into femtosecond and short pulse for pulses in the nanosecond regimes. In this study, the focus is on the threshold between "warm" and "cold" ablation. Different dielectric materials such as diamond and sapphire will be discussed. A generic and fast model based on multiple rate equations will be introduced. It provides important information like ablation threshold, ablation depth and optical properties. The model is a set of coupled ordinary differential equations (ODE), which describes the transient free electron density. In Figure 1, all three involved absorption mechanisms are illustrated. Initially, seed electrons are excited to the conduction band by multiphoton ionisation. Afterwards, electrons gain momentum through inverse bremsstrahlung, in which these so-called kinetic electrons can excite further electrons by impact ionisation.

The multiple rate equations are defined as "Domain ODE" in a 1-dimensional geometry. The intensity of the incident light field is assumed to be Gaussian distributed in the time domain. Light absorption inside the medium is described by the Lambert-Beer law. Multiphoton ionisation and inverse bremsstrahlung are strongly coupled to the intensity. On the one hand, these processes directly affect the absorption coefficient while on the other hand, they depend on the intensity. Therefore, intensity is calculated by solving a Weak Form PDE.

In Figure 2, the intensity of a laser pulse is depicted as function of time and space. This example shows a τp = 10 ps pulse (FWHM) centred at 20 ps with a fluence of 25 J/m2. Due to absorption, the intensity decreases with penetration depth.

Figure 3 shows the conduction band electron density distribution, which is the sum of the solutions of the Domain ODEs. The electron density saturates when the incident laser pulse reaches its maximum intensity. The electron density, similar to intensity, also declines with penetration depth.

Figures used in the abstract

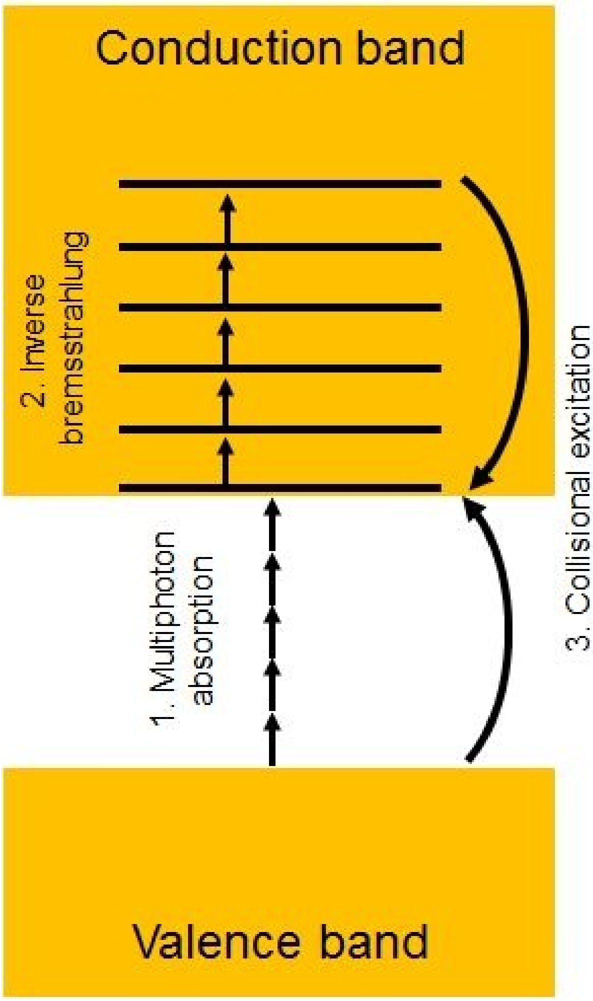

Figure 1: Schema of the electronic excitation in a dielectric material.

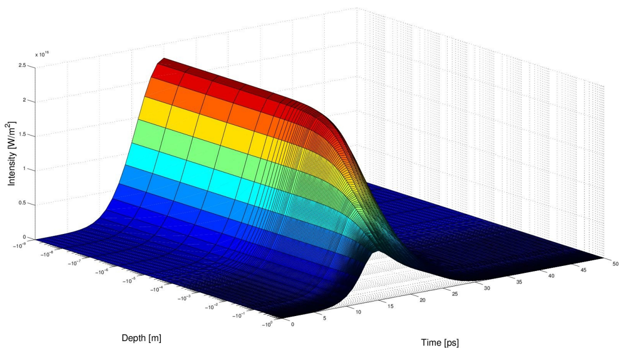

Figure 2: Light propagation through excitet dielectric material.

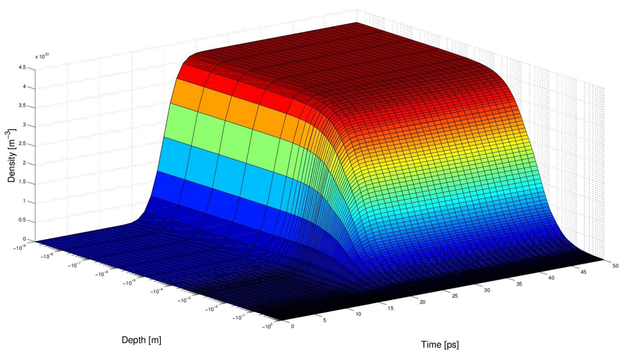

Figure 3: Calculated electron density as a function of penetration depth and time.